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(14) DOCUMENT NO. D2-90171 (6)

UNCLASSIFIED TITLE THE TRANSIENT BEHAVIOR OF TRANSISTORS DUE TO IONIZING RADIATION PULSES

MODEL NO. RESEARCH CONTRACT NO.

ISSUE NO. 19 ISSUED TO 7 Sgt R. G. Sykes Jr

CLASSIFIED TITLE
(STATE CLASSIFICATION)

| 23552 | 2-5471 | 32229 |
| --- | --- | --- |
| WORK ORDER NO. | UNIT NO. | ITEM NO. |

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NO. OF PAGES 27 (EXCLUDING TITLE AND REVISION AND ADDITION PAGES.)

DOCUMENT TITLE PAGE

U3 4010 5000

## PREFACE

This document contains a technical paper which resulted from work performed under U.S. Air Force contract AF 33(616)-7804 and under Boeing company-sponsored research. The paper has been accepted for presentation at the AIEE Summer General Meeting in Denver, Colorado, June 18-22, 1962.

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THE TRANSIENT BEHAVIOR OF TRANSISTORS DUE TO IONIZING RADIATION PULSES


ABSTRACT

The detailed mechanism of secondary photocurrent generation in transistors due to short pulses of ionizing radiation is discussed quantitatively and the results of *(0.2 μsec) flash X-ray experiments are explained. The dependences of the transient current pulse on transistor types, radiation dose, initial bias level, and external circuit impedance are presented. A possible equivalent circuit controlled by stored base charges is developed which makes it possible to predict more accurately the transient responses of many transistor circuits.

* - 0.2 microsecond


INTRODUCTION

The effects of the prolonged exposure of transistors to nuclear radiation have been studied for a number of years and several authors[1-7] have published accounts of their work. It is well established that the gamma ray component of radiation produces temporary ionization effects, whereas neutrons cause permanent damage to the semiconductor material, resulting in reduction of the carrier lifetime and the degradation of several critical transistor parameters, notably $\alpha$ and $I_{co}$. In contrast to the latter well understood situation, relatively little consideration has been given to the behavior of a transistor exposed to a short, intense dose of ionizing radiation, where important transient effects might be expected.

When transistors in the grounded emitter configuration were exposed to 0.2 μsec pulses of radiation from the Boeing flash X-ray facility, large current pulses having durations of several μsec or more were observed. These results could not be explained directly on the basis of current carrier generation in the depletion region or adjacent portions of the transistor, and therefore additional mechanisms were sought to explain the presence of the long current after-pulse. McKay[8] has observed similar effects in transistor type structures when exposed to alpha particles. He refers to this current as a secondary photocurrent as distinguished from the primary current flowing in the depletion region at the time of the radiation pulse. It is postulated that the production of carriers in the transistor will cause a temporary accumulation of majority carriers in the base region which tends to forward bias the emitter junction and thus produce the secondary photocurrent. The present report will summarize the original work reported earlier[9,10] and present some additional recent observations.

In the first section of this paper a theoretical analysis of the details of the photocurrent generation will be presented which allows quantitative estimates to be made of the expected behavior of many types of transistors under various operating conditions when irradiated with short pulses of ionizing radiation. The next section will contain experimental results obtained with the flash X-ray and a detailed comparison of these results with the theoretical predictions. The close agreement between theory and experiment allows the development of an equivalent circuit which is described in the third section. The essential behavior of this circuit is controlled by the flow of charges in and out of the base region of the device. This circuit representation makes it now possible to predict the transient response of many circuit applications.

THEORETICAL ANALYSIS

Charge Buildup in Base Region

In order to explain the effects of short pulses of X-rays on transistors, let us consider first the case of the 2N336 n-p-n silicon grown-junction transistor operated with the base open and uniformly irradiated for 0.2 μsec. We wish to calculate the collector (or emitter) current as a function of time. The following sequence of events will be

assumed:

1. Hole-electron pairs are created uniformly by the radiation throughout all three regions of the transistor.
2. In the base (for an n-p-n), electrons diffuse to the collector junction and are collected. Holes are left behind to form a positive excess charge.
3. In the collector body holes diffuse to the collector junction and drift across to the base region, thus increasing the excess positive charge in the base.
4. The total excess majority carrier charge in the base forward biases the emitter junction, resulting in minority carriers (electrons) flowing nearly simultaneously into the base from the emitter. These carriers compensate for the excess base charge and provide space charge neutrality.
5. The injected minority carriers (electrons) diffuse to the collector junction and are swept out by the reverse bias field thus contributing to the external current as long as the excess majority charge remains stored in the base region. Because the collector diffusion length, $L_p$, is much greater than the base width in the 2N336, the number of holes available in the base from process (3) greatly exceeds that from (2). Thus, we must investigate hole current into the base from the collector.
6. Hole-electron recombination in the base and collector is a continuous process which competes with the charge buildup in the base and which ultimately takes over.

We may calculate the total positive charge flowing from collector to base by making use of the diode results of W. L. Brown[11] who calculates a hole current, $i_p$, of

$$i_p = qgL_p \operatorname{erf}\left(\frac{t}{\tau_p}\right)^{1/2} \qquad \text{for } t < t_p \qquad (1a)$$

$$i_p = qgL_p \left[\operatorname{erf}\left(\frac{t}{\tau_p}\right)^{1/2} - \operatorname{erf}\left(\frac{t - t_p}{\tau_p}\right)^{1/2}\right] \qquad \text{for } t > t_p \qquad (1b)$$

where

$q = 1.6 \times 10^{-19}$ coulombs

$g$ = generation rate (assume 200 mr dose in silicon)

$= 10^6$ rad/sec $\times 7 \times 10^{13}$ pairs/cm$^3$ - rad

$= 7 \times 10^{19}$ pairs/sec - cm$^3$

$L_p$ = diffusion length for holes in collector

$t_p$ = length of ionizing pulse $= 2 \times 10^{-7}$ sec

$\tau_p$ = hole lifetime in collector $\cong 2$ μsec

Note that uncertainty in $g$ due either to inaccurate data on radiation rate or generation efficiency will affect the magnitude of the result, but not the time dependence. The time dependence is, however, closely related to $\tau_p$ which is generally not accurately known.

The total charge, $\Delta Q$, passing into the base is given by

$$\Delta Q = \int_0^\infty i_p(t)\,dt \qquad (2)$$

Graphical integration shows that for $\tau_p = 2$ μsec, 95% of the total charge has entered the base after 1.0 μsec. This is illustrated in Fig. 1, where the hole current, $i_p$, and the

charge, $\Delta Q$, are plotted as function of time from equations (1) and (2).

In addition to holes flowing in from the collector, electrons leave the base by diffusion to the collector junction, thus further increasing the net positive charge in the base. Without calculation, we might expect the excess charge originating in the base to amount to about one sixth of the total ([illegible]) and for it to accumulate in a time of the order of several transit times, that is, as soon as the incident pulse is over. This contribution is also shown in Fig. 1.

Evidently the excess charge in the base will forward bias the emitter, cause current to flow and thus produce the observed current pulse. Since the base transit time, $t_{\eta}$, is about $10^{-8}$ sec, corresponding to an alpha cut-off frequency of 15 mc, we would expect the emitter forward voltage and hence the external current to follow the charge buildup in the base, and hence to reach a maximum one or two microseconds after the X-ray pulse. Recombination processes will later cause the current to decay.

Several consequences of the above theory and calculations may be deduced from elementary considerations. In the first place, since we are dealing with a transistor whose emitter is slightly forward biased by the applied collector-to-emitter voltage, any increase in the emitter-to-base voltage will result in an exponential increase in the current. However, this latter voltage in a transistor is insensitive to large changes in the applied collector voltage so long as the rated breakdown voltage is not approached too closely. Secondly, the total charge accumulated in the base is proportional to the integrated radiation dose provided $t_{\eta} \ll \tau_{p}$. Hence, a very strong dependence of photocurrent on radiation intensity should be observed. The relation will not be exponential because, as will be shown later, the charge-voltage relation at the emitter is non-linear.

Distribution of Charge in Base

We now wish to investigate in detail the physical processes which occur at the emitter junction and in the base due to charge confinement in the base. This will lead to a discussion of the roles of the depletion layer capacitance and of the diffusion capacitance. Ultimately we wish to calculate the peak photocurrent which will result from a given dose of radiation.

Consider the disposition of the excess charge. Since these excess charges are majority carriers, they will rearrange themselves in the order of $10^{-10}$ seconds (i.e., instantaneously) in such a way that there is no field in the base region. Thus, uncompensated charges can exist only at or near the "surface," that is, on the depletion layer capacitances. We must think of some of the excess holes in the base of an n-p-n transistor as neutralizing some of the negatively charged atoms which form the base side of the depletion layer capacitance, thus bringing the "plates" of the "capacitor" closer together and increasing the capacitance. Thus, the forward voltage across the emitter junction is increased and the current through the junction increases.

We will now calculate the base charge, $\Delta Q_1$, required to change the voltage across the depletion layer and compare it with that available due to the X-rays. In the 2N336 the emitter depletion layer capacitance, $C_1$, varies with voltage as shown in Fig. 2, in which 0.75 volts are added for the built-in potential, $V_o$. The emitter junction is assumed to be biased initially at a typical value of 0.18 volts forward and to obey the equation for an ideal diode. Thus we arrive at Table I relating $I_o$, $V_{BE}$, $C_1$ and $\Delta Q_1$.

In addition, the collector-to-base voltage changes by the same amount as $V_{BE}$ and the collector capacitance must also be charged. Since $\Delta Q_c = C_c \times \Delta V_c \cong 7 \times 10^{-12} \Delta V_c$, there results about a 10% correction to $\Delta Q_1$ at $I_c = 1$ ma. This correction will be neglected.

TABLE I. Calculated Current Dependence of Charge Stored on Depletion Capacitance (2N336)

| $I_c$ (ma) | $V_{pn}$ (volts) | $C_1$ ($\mu\mu f$) | $\Delta Q_1$ (coul) |
|---|---|---|---|
| $2 \times 10^{-6}$ | +0.18 | 45 | -- |
| $10^{-4}$ | 0.31 | 48 | $6 \times 10^{-12}$ |
| $10^{-3}$ | 0.375 | 51 | 10 |
| $10^{-2}$ | 0.44 | 54 | 15 |
| $10^{-1}$ | 0.52 | 60 | 22 |
| 1 | 0.58 | 66 | 30 |
| 10 | 0.67 | 90 | 51 |

The charge available due to irradiation may be calculated as follows. Since the bar is ~0.32 mm square, the junction area is $10^{-3}$ cm$^2$. Then from Fig. 1, based upon a 200 mr dose, $Q_{rad} = 4 \times 10^{-9} \times 10^{-3} = 4 \times 10^{-12}$ coulomb at t = 0.2 μsec and approximately $10 \times 10^{-12}$ coulomb at 1 μsec. Thus, since photocurrents of the order of 0.15 ma are observed at this dose, there is fair agreement between the charge available and that required to charge depletion layer capacitance as listed in Table I.

It is apparent that as soon as electrons begin to enter the base from the emitter, they will neutralize some of the excess holes on the base side of the depletion layer. There will in fact be set up a gradient of electrons in the base corresponding to the current flow. Since there must be space-charge neutrality in the region removed from the depletion layer, the majority carriers will rearrange themselves continuously. This means that some of the excess holes will never go to the depletion layer. Thus, at every instant, the total number of excess holes in the base must be the sum of those accumulated on the depletion layer, $\Delta Q_1$, plus those paired with electrons in transit by diffusion across the base, $\Delta Q_2$. This latter number may be easily calculated, either by an integration involving the diffusion capacitance or directly from the current in the following manner. We have

$$I = q D_n \frac{\partial n}{\partial x} A \tag{3}$$

If I = 0.15 ma, the electron concentration gradient is then

$$\frac{\partial n}{\partial x} = 2.3 \times 10^{16}/\text{cm}^4$$

for a 2N336. The charge, $\Delta Q_2$, in transit across the base is

$$\Delta Q_2 = q A w \bar{n} = q A w \frac{w}{2} \frac{\partial n}{\partial x} \tag{4}$$

$$= (1.6 \times 10^{-19})(10^{-3})(10^{-3})(0.5 \times 10^{-3})(2.3 \times 10^{16})$$

$$= 1.8 \times 10^{-12} \text{ coulomb}$$

The total calculated charge, $(\Delta Q_1 + \Delta Q_2)$, required to support a current of 0.15 ma is then approximately 25 μμ coulomb. This compares fairly well with the 10 μμ coulomb produced by radiation.

In the above description of the processes in the base region, there was a somewhat arbitrary division of excess charge between depletion layer and diffusion capacitances. It must be emphasized that the total excess base charge is utilized simultaneously in turning the emitter junction on and neutralizing the resulting minority carriers as they enter the base. The times involved are all extremely short; for example, holes move across the base in perhaps $10^{-10}$ seconds and electrons cross the emitter barrier in about the same time, while electrons (in the 2N336) diffuse across the base in about $10^{-8}$ seconds. These times may be compared with the $10^{-6}$ seconds required for the accumulation of excess base charge. It is apparent that in the 2N336 all processes except base charge accumulation are effectively simultaneous and instantaneous.

Comparison of Transistor Types

All of the above calculations may be repeated for other types of transistors with only minor modification. We will illustrate by considering the charge buildup in the bases of the following two devices:

1. A p-n-p germanium alloy transistor having $\tau_p$ (base) = 20 μsec, $\tau_n$ (coll) ≈ 0.1 μsec (estimate), $D_n$ = 10, and $w = 3.5 \times 10^{-3}$ cm ($f_\alpha$ 1 mc). The value for $D_p$ is based on the assumption that the mobility $\mu \approx 400$ cm$^2$/volt-sec at acceptor concentrations of $10^{18} - 10^{19}$ cm$^{-3}$ in the emitter and collector. Then $D_p/\mu = kT/q = 1/40$. Data on μ values are from E. Conwell[12]. Then $L_p = (45 \times 20 \times 10^{-6})^{1/2} = 0.03$ cm, $L_n = (10 \times 10^{-7})^{1/2} = 10^{-3}$ cm. The base width, w, is approximately 0.1 $L_p$ and 3.5 $L_n$.
2. A p-n-p germanium alloy power transistor with similar $L_p$ and $L_n$ to those in (1) above but with a much greater base width, w.

In device (1) the base is three or four times as wide as $L_n$ in the collector so that the contribution to total charge from holes leaving the base should be dominant over that due to electrons arriving from the collector by about the same factor. The base transit time is $t_d = w^2/2\,D_p = 1.3 \times 10^{-7}$ sec. Thus, all charge should be accumulated within 0.1 or 0.2 μsec of turn-off of the X-rays and the current peak should be attained in the same time.

The same arguments apply to the power transistor except that the base transit time is larger and hence the time-to-peak of the base charge and of the current pulse is larger also. Table II summarizes the significant information estimated for all types of alloy transistors. Note that the base contribution to total base charge is dominant except in the last two cases, where the base thickness, w, is of the same order as $L_n$.

TABLE II. Estimated Time-to-Peak for Various Alloy Transistors

| $f_\alpha$ | $t_d$ | Est. $\tau_p$ (base) | Est. Time-to-Peak |
|---|---|---|---|
| 5 kc | 30 μsec | 300 μsec | 30 - 60 μsec |
| 10 | 16 | 300 | 15 - 40 |
| 70 | 2.3 | 75 | 2 - 6 |
| 100 | 1.6 | 50 | 1.5 - 4 |
| 500 | 0.3 | 30 | 0.5 - 1.0 |
| 1 mc | 0.16 | 20 | 0.35 - 0.6 |
| 5 | 0.032 | 5 | 0.3 |
| 10 | 0.016 | 5 | 0.3 |

The calculation of the charges, $\Delta Q_1$ and $\Delta Q_2$, on the depletion-layer and diffusion capacitances respectively and of the charge, $Q_{rad}$, produced by radiation proceeds in the same way as for the 2N336. The results for four transistors on which extensive experimental data are available are shown in Table III. The current $\Delta I_{max}$ is that which is typically observed for a dose of 200 mr. The agreement between the charge assumed to have been produced by radiation and that required to produce the observed currents is excellent considering the ranges and possible errors involved. The fact that the ratio $(\Delta Q_1 + \Delta Q_2)/Q_{rad}$ is always greater than unity may indicate that the estimates of radiation intensity are low, but such a result may be fortuitous since the junction areas, capacitances, etc. are not very well known.

Because of the importance of the diffusion capacitance in certain situations, it is desirable to evaluate it for the devices we are considering. It is shown by van der Ziel[13] and by Early[14] that the emitter diffusion capacitance, $C_2$, of a transistor is given by

$$C_2 = g_{eo}/1.5\,\omega_\alpha \tag{5}$$

where

$$g_{eo} = \frac{q\,I_c}{kT} \text{ mhos} \tag{6}$$

is the d.c. conductance of the emitter junction. Equation (5) is valid for frequencies below $f_\alpha$ ($\omega_\alpha = 2\pi f_\alpha$). Above $f_\alpha$, $C_2$ decreases with increasing frequency. Table IV gives $C_2$ for four of the devices under investigation over a wide range of operating conditions.

## EXPERIMENTAL RESULTS

It is now possible to apply the basic ideas outlined above in order to predict certain properties of a transistor under irradiation. Let us first consider the current and voltage buildup, then the effects of recombination on the pulse decay, the dependence of current on radiation rate and bias, the device behavior when the base is not open circuited, saturation effects and the effect of a transverse base resistance.

TABLE III. Calculated Charges in Various Transistors Resulting from a 200 mr X-ray Pulse.

| | 2N336 | 2N393 | 2N1099 | W. E. Alloy |
|---|---|---|---|---|
| Base width (cm) | $10^{-3}$ | $5 \times 10^{-4}$ | 0.014 | $4 \times 10^{-3}$ |
| Emitter Area ($cm^2$) | $10^{-3}$ | $2 \times 10^{-4}$ | 0.13 | $1.2 \times 10^{-3}$ |
| Collector Area ($cm^2$) | $10^{-3}$ | $4.5 \times 10^{-4}$ | 0.75 | $5 \times 10^{-3}$ |
| $\Delta I_{max}$ (ma) | 0.15 | 4 | 170 | 30 |
| $\Delta Q_1$ (μμ coul) | 23 | 2 | 200 | 5 |
| $\Delta Q_2$ (μμ coul) | 2 | 100 | $3.3 \times 10^5$ | 5000 |
| $\Delta Q_1 + \Delta Q_2$ (μμ coul) | 25 | 100 | $3.3 \times 10^5$ | 5000 |
| $Q_{rad}$ (μμ coul) | 10 | 15 | $2.5 \times 10^5$ | 500 |
| $(\Delta Q_1 + \Delta Q_2)/Q_{rad}$ | 2.5 | 6.6 | 1.3 | 10 |

TABLE IV. Calculated Current Dependence of Diffusion Capacitances for Four Transistor Types.

| | | $C_2$ ($\mu\mu f$) | | | |
|---|---|---|---|---|---|
| I (ma) | $G_{co}$ (mhos) | 2N336 | 2N393 | 2N1099 | W. E. Alloy |
| $2 \times 10^{-6}$ | $8 \times 10^{-8}$ | $5 \times 10^{-4}$ | | | |
| $10^{-4}$ | $4 \times 10^{-6}$ | 0.025 | | | |
| $10^{-3}$ | $4 \times 10^{-5}$ | 0.25 | | | 4 |
| $10^{-2}$ | $4 \times 10^{-4}$ | 2.5 | 0.8 | | 40 |
| $10^{-1}$ | 0.004 | 25 | 8 | | 400 |
| 1 | 0.04 | 250 | 80 | 0.06 $\mu f$ | 4,000 |
| 10 | 0.4 | 2500 | 800 | 0.57 $\mu f$ | 40,000 |
| 25 | 1.0 | | 2000 | 1.4 $\mu f$ | |
| 50 | 2.0 | | 4000 | 2.8 $\mu f$ | |
| 100 | 4.0 | | | 5.7 $\mu f$ | |

## Current and Voltage Buildup

Figure 3 shows typical simultaneous current and voltage pulses obtained from a 2N336 n-p-n silicon grown-junction transistor. The transistor was operated with an external base-to-emitter resistance, $R_{BE}$, of 100 K and the current was monitored with a low impedance current probe which was placed in the collector-emitter bias circuit. The voltage, $\Delta V_{BE}$, was measured using a high impedance probe between base and emitter contacts. The associated flash X-ray pulse was also monitored and showed that the X-rays start at the same time that the transistor pulses start to rise and that the X-ray pulse duration was approximately 0.2 µsec. From the Figure we see that the current and voltage both continue to rise for nearly 1 µsec as expected from the calculated charge buildup in a grown-junction device.

We also observe in Fig. 3 that the voltage peaks at a later time than does the current. The observed delays vary from 0.0 to 1.0 µsec being larger for smaller initial bias levels. This delay is believed to be due to the presence of a fairly high transverse base resistance in the 2N336. (This resistance is evidenced by some additional measurements described below where an apparent reverse bias is observed on the emitter junction even though forward current is flowing.) The transverse base resistance will cause the observed delay in the peak of the measured voltage pulse, $\Delta V_{BE}$, if an external base-to-emitter capacity, $C_{BE}$, is present since the measured voltage will then lag the internal base-to-emitter voltage, $\Delta V_{be}$, which determines the observed collector current.

Other transistor types (p-n-p germanium alloy devices) show similar buildups of current pulses. The peak buildup times for all transistor types measured thus far vary from 0.6 µsec up to about 7.0 µsec as shown in Table V. A comparison of these times with the values calculated in Table II on the basis of the quoted $f_\alpha$ shows order-of-magnitude agreement but probably the discrepancies can be attributed to the lack of exact knowledge of the pertinent carrier lifetimes and dimensions of each individual transistor type.

## Effect of Recombination

It is clear that, in the base, the excess charges will recombine with charges of the opposite sign which are in transit from emitter-to-collector. In the three germanium alloy

TABLE V. Comparison of Transient Current Pulses Obtained from Various Transistors

| Transistor Type | Quoted $f_\alpha$ (mc) | Peak $I_{ceo}$ at 200 mv (ma) | Time to Peak (μs) | Decay Time (μs) | Measured Base Minority Carrier Lifetime[15] (μs) |
|---|---|---|---|---|---|
| PNP Alloyed Germanium at 6.4 V: | | | | | |
| 2N1099 | 0.07 | 300 | 7.0 | 68 | 72 |
| 2N174 | 0.07 | 300 | 0.7 | 47 | 51 |
| 2N369 | 1 | 40 | 1.7 | 11.2 | 9.65 |
| 2N393 | 8 | 35 | 0.7 | 1.4 | 1.59 |
| 2N525 | -- | 20 | 1.0 | 7.0 | 5.99 |
| 2N269 | 12 | 15 | 0.6 | 0.7 | 1.13 |
| 2N370 | 30 | 13 | 0.6 | 1.5 | 1.38 |
| 2N384 | 100 | 6.5 | 0.8 | 0.5 | 0.56 |
| NPN Grown Silicon at 6 V: | | | | | |
| 2N336 (TI) | 15 | 0.15 | 0.6 | 1-2 | 2-3 |
| 2N336 (GE) | 15 | 2 | 2 | 4 | 1.5 |

transistors already discussed (2N393, 2N1099, W. E. Alloy) almost all the excess majority carriers in the base are required to neutralize the minority carriers in transit. That is, for p-n-p transistors:

$$n_{excess} = p_n \qquad \text{(Alloy Devices)} \quad (7)$$

Thus the lifetime of the excess charges is just the minority carrier lifetime, $\tau_p$, in the base. Since the current is at any instant proportional to the number of minority carriers in the base, it follows that the current will decay exponentially with a time constant equal to $\tau_p$.

The last two columns of Table V show the comparison between the observed decay constants of the current pulses for different transistor types and the minority carrier lifetimes for the base regions as measured by the method of Beaufoy and Sparkes[15]. For the alloy devices excellent agreement is obtained thus supporting the expectation that the current decay is controlled by the base minority carrier lifetime whenever the diffusion capacitance is large compared to the emitter depletion capacitance.

The frequency dependence of the emitter diffusion capacitance may produce an observable result in a transistor with a very low alpha cut-off frequency such as the 2N1099. In that device the initial rush of minority carriers from the base to the collector by diffusion will result in an equally sudden influx of base minority carriers from the emitter. Their gradual motion across the base will correspond to the gradual increase in $C_D$. We may accordingly expect to see a base-to-emitter voltage that decreases suddenly for a time of the order of $1/f_\alpha$ and then continues to decay more slowly thereafter as a result of the

usual recombination processes. Preliminary measurements of the photovoltage, $\Delta V_{BE}$, in the 2N1099 have shown a rather sharp drop during the first few microseconds followed by a more normal decay. This behavior is at least qualitatively in agreement with the expected frequency dependence of the diffusion capacitances in this device.

For the 2N336, however, a substantial fraction of the excess majority carriers (holes) are in the depletion layer. Since they are neutralized by ionized acceptor atoms rather than by free electrons, they do not affect the recombination rate. Thus, we expect (1) the current to decay more slowly than the minority carrier lifetime, $\tau_n$, would indicate, and (2) the decay time should be longer at lower currents, because a larger proportion of the excess carriers are then located on the depletion layer. Such behavior is in fact observed (Table V) for one brand of 2N336 (General Electric) but the results are questionable for the other (Texas Instruments) largely due to uncertainty in the lifetime measurement. Reproducibility in the measurements could not be achieved for this particular transistor. The expected dependence of decay time on initial current level, $I^o{}_c$, has been observed as shown in Fig. 4 for a typical unit.

Also shown in these figures are the corresponding base-to-emitter voltages which, in each case, decay more slowly than do the corresponding currents. This result is expected for the 2N336 where $C_1 > C_2$, since the current can then become an exponential function of the voltage. It is further interesting to note that the lower currents give higher photovoltages. This is caused by the lower diffusion capacitance (proportional to current) permitting a larger fraction of the total charge (constant in each case) to appear on the nearly constant depletion capacitance.

In Fig. 5 the decaying current as a function of the photovoltage is plotted for this same transistor as well as for the Western Electric alloy unit. It can be seen that the voltage decays at the rate of 50 to 70 millivolts per decade of current, which is very nearly the expected value of 60 mv/decade for a forward biased p-n junction at 300° K as calculated from the relation:

$$I = I_o \exp\left(\frac{qV}{kT}\right) \tag{8}$$

Effects of Radiation Dose

Another result of the fact that in the alloy transistors most of the excess charges are required to neutralize minority carriers in transit is that the peak current following irradiation should be proportional to the total dose (for doses delivered in times short compared to the lifetime). This follows from the linear dependence of excess charge on total dose, and from the fact that current is proportional to the total number of minority carriers in the base.

If, however, a transistor were operated in such a way that most of the excess charge was on the depletion layer instead of neutralizing minority carriers, the above conclusion would not be valid. Since the change in voltage, $\Delta V_{BE}$, across the emitter junction is given by

$$\Delta Q_1 = C_1 \Delta V_{bo} + V_{bo} \Delta C_1 \tag{9}$$

where the latter term is negligible if $C_1$ is nearly constant, and since the current follows the diode equation,

$$I = I_o (e^{qV/kT} - 1) \quad , \tag{10}$$

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it follows that in this extreme case (where $C_1 >> C_2$) we would expect the peak current to be an exponential function of total dose for fixed initial bias current.

This conclusion might be slightly modified by the fact that the depletion layer capacitance is a function of voltage. Since the 2N336 lies between the alloys and the above extreme, one might expect intermediate behavior. Table VI indicates the relative significance of $\Delta Q_1$ and $\Delta Q_2$ at different current levels in the 2N336. Above 10 ma the same bias and radiation dependences hold as in the alloy case, whereas below 1.0 ma we approach the extreme case described above.

Figure 6 shows the dependence of the peak photocurrent on the received dose for three types of transistors. The 2N1097 and the 2N393 are both p-n-p germanium alloy transistors and exhibit a linear dose dependence because of the predominance of the diffusion capacitance in these devices.

For the 2N336, however, the diffusion capacitance should not predominate below 10 ma so that at the lower initial current levels the photocurrent should rise exponentially with increasing dose. Figure 6 shows this to be approximately the case with the current increasing ten-fold for a dose increase of only a factor of two. Actually, an exponential increase would not be a straight line as shown in Fig. 6 but rather would increase a little more steeply as the dose levels increase. That such a steep rise is not observed could partly be due to scatter in the data and partly due to the onset of a more linear dose dependence at the higher current levels.

Effect of Initial Bias Level

In transistors for which $C_2 >> C_1$ the same arguments can be used to show that if devices are biased at two different currents, $I_a$ and $I_b$, the same radiation dose will cause equal increments in current. That is $\Delta I_a = \Delta I_b$. On the other hand, if the depletion layer capacitance, $C_1$, is dominant, the change in current, $\Delta I$, will be a linear function of initial bias current for fixed total dose. That is $\Delta I_a = (I_a/I_b)\Delta I_b$.

Experimentally, these conclusions are verified. In Fig. 6 the photocurrents are seen to be independent of initial bias for the 2N393. However, the photocurrent in the 2N336, in contrast to the behavior of the alloy device, is not independent of the initial bias level as shown in Fig. 7; instead, it increases slowly as the initial collector current is increased. This dependence, which is intermediate between a linear variation ($C_1$ dominant) and a constant value ($C_2$ dominant), is expected since the observed photocurrents of from 1 to 30 ma cause the effective values of $C_1$ and $C_2$ to be of the same order of magnitude. At lower radiation doses the dependence on initial bias level would be more pronounced.

TABLE VI. Calculated Current Dependence of Relative Charge Storage on Depletion and Diffusion Capacitances in a 2N336.

| $I_c$ (ma) | $\Delta Q_1$ (coul) | $\Delta Q_2$ (coul) |
|---|---|---|
| 0.01 | $15 \times 10^{-12}$ | $0.12 \times 10^{-12}$ |
| 0.1 | 22 | 1.2 |
| 1.0 | 30 | 12 |
| 10 | 51 | 120 |
| 100 | 90 | 1200 |

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## Effect of an External Base-to-Emitter Resistance

The role of the diffusion capacitance, $C_2$, in controlling the current decay in certain circuit applications where the base is not open, can now be explained. Once a current has been set up in a transistor, a change in it corresponds to a change in the number of minority carriers in the base. Hence, the diffusion capacitance must be charged or discharged by current flow into or out of the base. If an external resistance, $R_{BE}$, is connected between base and emitter, we may expect a current decay with a time constant $\tau = (R_{BE}+r_b)C_2$ where $r_b$ is the internal base resistance.

Consider the 2N1099 for which $C_2 \cong 1$ µf at 20 ma. Thus we have decay times of 1 millisecond for $R_{BE}$ = 1000 ohms and 10 µsec for $R_{BE}$ = 10 ohms. In the first instance, the decay time would certainly be determined by recombination since the base lifetime equals 68 µsec, while in the second case it would be determined by the external circuit. The internal resistance, $r_b$, associated with the base region in a 2N1099 is reported to be of the order of 10 ohms.

For the 2N1099 it has been found that varying the external base-to-emitter resistance, $R_{BE}$, has no significant effect on the peak value of the photocurrent as shown in the upper curve of Fig. 6 where the experimental points represent (in random order) $R_{BE}$ values ranging from 0 to $\infty$ ohms. This result is expected because of the short buildup time in this device compared to its long decay time whether it be due to recombination ($\tau_p$ = 68 µsec) or to external discharge of the diffusion capacitance which is large. However, when the $R_{BE}$ drops low enough for $[(R_{BE} + r_b)\, C_2]$ to be of the order of 100 µsec or less than the pulse decay time will decrease. Actual measurements of a series of current traces illustrate this latter behavior. The decay times, scaled from these traces for various values of $R_{BE}$, are shown in Table VII and may be used to calculate the values of the internal base resistance, $r_b$, and the diffusion capacitance, $C_2$, from the relation for the decay time, $\tau_d$:

$$\frac{1}{\tau_d} = \frac{1}{\tau_p} + \frac{1}{(R_{BE} + r_b)\, C_2} \qquad (11)$$

where the base lifetime, $\tau_p$, is approximately 68 µsec. The values obtained from such a process are $r_b \cong 10$ ohms and $C_2 \cong 0.6$ µf. These results (obtained from current pulses decaying from 300 ma to 2 ma) are in excellent agreement with the values predicted above and in Table IV.

TABLE VII. Current Decay Time as a Function of External Base-to-Emitter Resistance for the 2N1099.

| $R_{BE}$ (ohms) | DECAY TIME, $\tau_d$ (µs) |
|---|---|
| 1 M | 66 |
| 100 K | 67 |
| 10 K | 68 |
| 1 K | 67 |
| 100 | 42 |
| 33 | 17 |
| 10 | 12.5 |
| 5 | 9 |
| 1 | 6 |
| 0 | 4 |

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In the 2N336 the diffusion capacitance is about 5000 µµf at I = 20 ma. This leads to time constants of 5 µsec and 0.05 µsec for $R_{BE}$ values of 1000 and 10 ohm respectively. As a consequence, the photocurrent pulse length for the 2N336 would be determined by the external circuit for all $R_{BE}$ less than about 200 ohms. Unfortunately, no accurate data have yet been obtained for this transistor for low values of $R_{BE}$ (around 200 ohms or so) at constant bias levels below saturation, but assorted pieces of information indicate that $R_{BE}$ has no effects at values down to as low as 600 ohms. The next section will present some data showing the effects of $R_{BE}$ on a saturated 2N336.

<u>Saturation Effects</u>

In all the preceding analyses, no restriction has been placed on the radiation intensity nor on the magnitude of the photocurrent. In most alloy devices where the collector resistivity is low, the only limitation on current will be the capability of the transistor to dissipate the resulting thermal energy. However, in a grown-junction device such as the 2N336 or in most diffused structures, there is a voltage drop in the collector body due to the significant resistivity of that region of the transistor. If this voltage drop equals the applied collector-to-base voltage, the transistor current will be saturated and will remain so until recombination in the base reduces it. At the same time, one must expect very strong conductivity modulation in the collector because of the large number of hole-electron pairs produced there by the X-rays. Hence, the resistance of the colector region will increase as these carriers recombine and the saturation current will gradually decrease with time.

In general, this type of behavior was observed in the 2N336 when irradiated with saturating doses above 3 roentgens. Figure 8 shows some of these current pulse decay curves obtained with various values of $R_{BE}$. The early part of the decay occurs while the device is saturated, with the current decreasing as the carriers recombine in the collector body, thus increasing its resistance and further limiting the flow of current. Eventually, at the "knee," "saturation" ends and the normal decay follows.

It is interesting to note that from a single graph such as Figure 8, it is possible to estimate both the resistance of the collector region and the minority carrier lifetime. The intrinsic collector resistance, $r_c$, may be found by dividing the applied voltage (6 volts) by the current at the transition point (40 ma). For this particular unit the calculation gives $r_c \approx 150$ ohms. This result compares favorably with the value of 100 ohms estimated from the assumed collector resistivity of 1 ohm-cm and the dimensions of $10^{-3}$ cm$^2$ by 1 mm. The collector lifetime, $\tau_p$, may be estimated since it controls the saturation current. At $R_{BE} = \infty$ the current would be proportional to $n_0 + \Delta n e^{-t/\tau_p}$ from which it appears that the collector lifetime is from 3 to 6 µsec.

The reduction of $R_{BE}$ is seen to result in a somewhat shorter effective decay time of the excess carriers in the collector and to cause the "knee" to occur earlier and at lower currents.

<u>Effect of Transverse Base Resistance</u>

When the base of a transistor is connected to the circuit through a low impedance, the majority carrier current flowing out of the base can cause an internal voltage drop across the transverse base resistance of the device. This action is similar to that encountered in a solid state tetrode. Although such a flow of majority carriers always develops a transverse voltage within the base region of any transistor, the magnitude of this voltage is accentuated in grown-junction transistors because of their high base resistance. For

this reason some effects of the transverse base resistance will now be considered for the 2N336 device.

Results of the effect described above were first noticed experimentally when the common collector configuration of a 2N336 amplifier circuit was irradiated in the environment of the Kukla test reactor at Livermore, California. During the 80-microsecond pulse from the reactor it was noted that both p-n junctions became temporarily reverse-biased even though a collector current of 8 ma was present. Figure 9 shows the details of the observed current and voltages at the peak of the pulse. It will be noted that during "forward" transistor current flow there was an apparent reverse bias of about 3 volts on the emitter-base junction and a normal reverse bias of about 19 volts on the collector-base junction.

To confirm the possibility that a transistor could pass a current in the forward direction through a reverse-biased emitter junction, the following experiment was performed with the flash X-ray source. The circuit used employed two external batteries to develop a reverse bias on each p-n junction, with the battery voltages (3 volts and 63 volts) being slightly less than those which would result in large currents in the external circuit (i.e., breakdown). These large voltages widen the depletion regions and thereby reduce the width of the nondepleted base region to a minimum, thus impeding the transverse flow of base current as much as possible and enhancing the magnitude of any transverse base voltage that might develop. Upon subjecting the transistor to approximately one roentgen of X-rays, an emitter current pulse of 0.5 ma was observed which flowed in the same direction as the d.c. current associated with a forward-biased junction. Since the external batteries maintain an apparent condition of reverse bias at the terminals of the device, it seems reasonable that a transverse voltage must be developing in the base as shown in Fig. 9 which permits a forward bias to exist at the region of the emitter-base junction which is furthest from the base lead. However, as one moves toward the base contact along the emitter-base junction, the size of the depletion region increases to the extent that a condition of reverse bias exists in that portion nearest to the base contact. The collector-base junction is everywhere reverse biased. The dual depletion regions cause a pinching effect in the base which sustains a rather large transverse potential during the burst of radiation. The transverse voltage in the base is a transient effect, decaying toward zero as the excess charge concentration decreases.

The magnitude of the expected transverse voltage drop can be estimated by considering a similar n-p-n structure, the 3N34 tetrode transistor. In this device, which is similar to the 2N336 in electrical characteristics such as cutoff frequency, etc., the resistance of the base region between the two base contacts has a design-center value of 10 K ohms. Thus this tetrode transistor requires a base-to-base current of only 100 μa to produce a transverse voltage of one volt in the base region. The results of the Kukla pulse reactor tests shown in Fig. 9 may be used to calculate the observed transverse base resistance. The emitter junction was initially forward biased 0.6 volts which, when added to the observed transient reverse bias of 2.82 volts, yields a transverse voltage of 3.42 volts. With an observed base current of 210 μa we obtain a value of 17 K for the effective transverse base resistance. This value compares very well with the value of 10 K expected for the similarly constructed tetrode device.

## EQUIVALENT CIRCUIT

The results of the effects discussed so far can now be used to construct an equivalent circuit for many transistors which should fairly well describe the quantitative time-dependent behavior of such devices when exposed to short pulses of ionizing radiation. The equivalent circuit should be amenable to insertion in an analog computer representation of a complete circuit which could be useful in predicting the circuit's response to transient

radiation pulses. The circuit presented will be generally applicable to many types of transistors but was developed in particular for the 2N336 device.

Figure 10 shows the simplified equivalent circuit and a block diagram of the analog computer functions necessary for its proper operation. The basic general procedure consists of inserting excess charge onto the emitter-base depletion and diffusion capacitances, $C_1$ and $C_2$ respectively, by means of the current generator, $i_p$, which represents the influx of excess majority carriers into the base. Simultaneously, these excess charges can leave the base by two mechanisms: either (1) by recombination with base minority carriers as represented by the negative current generator, $i_r$, or (2) by flowing through the transverse base resistance, $r_{bt}$, and out the base lead, B, to the emitter, E, through the external base-to-emitter impedance which, in this case, includes only $R_{BE}$ and $C_{BE}$ in parallel. The resulting time-dependent internal base-to-emitter photovoltage, $\Delta V_{be}$, is then used to generate the transient collector current, $I_c$, which in turn is used to alter continuously the value of the current-dependent diffusion capacitance, $C_2$. The observed external base-to-emitter photovoltage, $\Delta V_{BE}$, may also be monitored.

Specifically, the time-dependent value of $i_p$ may be obtained exactly from equations (10) and (11) which, for the 2N336, defines the major contribution of primary hole current which charges the base region. The recombination current, $i_r$, is determined by the excess charge on $C_2$ only and is given by

$$i_r(t) = \frac{\Delta Q_2(t)}{\tau_b} \tag{12}$$

where the value of $\Delta Q_2(t)$ is determined by the instantaneous value of the photovoltage, $\Delta V_{be}(t)$, according to the relation

$$\Delta Q_2(t) = C_2^o \left[ e^{\frac{q}{kT}\Delta V_{be}(t)} \left( V_{be}^o + \Delta V_{be}(t) \right) - V_{be}^o \right] \tag{13}$$

Equation (13) is obtained from equation (5) and basic principles. $\Delta V_{be}(t)$ is also used to determine the resulting collector current, $I_c(t)$, according to

$$I_c(t) = I_c^o \, e^{\frac{q}{kT}\Delta V_{be}(t)} \tag{14}$$

which, in turn, determines $C_2(t)$ through

$$C_2(t) = C_2^o \left( \frac{I_c(t)}{I_c^o} \right) \quad . \tag{15}$$

In the above procedure certain assumptions have been made for reasons of simplicity as follows:

1. The primary photocurrent of holes from emitter-to-base is negligible compared to that from collector-to-base.
2. The primary photocurrent of electrons leaving the base is negligible compared to $i_p$.
3. The variation of $C_1$ during the transient is negligible.
4. The collector depletion capacitance is small compared to $C_1$.
5. It is unnecessary to consider the parameters $C_1$, $C_2$ and $r_{bt}$ as being distributed along the transverse direction.

6. The emitter body resistance is negligible.
7. High-level injection does not occur.

For the unsaturated 2N336 these assumptions are sufficiently valid but for other transistors each would have to be re-evaluated.

## CONCLUSIONS

A series of experimental observations, supported by a quantitative theoretical analysis has defined the essential features of the response of a transistor to a short pulse of X-rays. The observed effects can be explained by the temporary storage of majority carriers on the depletion-layer and diffusion capacitances associated with the emitter junction.

Specific observations which lead to this conclusion are the following:

1. A delayed buildup of the secondary current pulse following flash X-ray irradiation. This delay is caused by the diffusion time of carriers from the collector body in grown-junction devices but by base transit time in low or medium frequency alloy types.
2. The transient current pulse can peak before the observed base-to-emitter voltage.
3. At low current levels, when depletion-layer capacitance predominates over diffusion capacitance, the peak current is almost exponentially dependent on the radiation dose received, whereas at higher current levels the diffusion capacitance is dominant and the peak current is linearly dependent on radiation dose.
4. An increase in initial bias level will increase the observed photocurrent at low current levels but will have little or no effect at higher currents.
5. In situations where the diffusion capacitance is dominant, the decay time constant of the current pulse is the same as the minority carrier lifetime in the base, provided that the external base-to-emitter impedance is sufficiently high.
6. For relatively low external base-to-emitter resistances the decay time constant of the current pulse is determined principally by the product of this resistance and the junction capacitances.
7. Saturation effects in the 2N336 can be explained by modulation of the collector body resistance.

The magnitude of the secondary photocurrent pulse may be estimated for various types of transistors from calculations of the available charge due to radiation. Such estimates have been found to be in good agreement with the observed pulses.

A simple equivalent circuit of the transistor follows naturally from the theoretical description of the processes which occur after irradiation. Thus the prediction of circuit behavior under similar radiation conditions is greatly facilitated.

In spite of the fact that a great deal of experimental and theoretical information has been obtained, much more work is necessary in order to characterize completely a transistor in a pulsed X-ray environment. In particular, it is necessary to extend the investigation to other types of devices, especially those with much higher frequency capabilities and with different geometries. Secondly, the effects of external circuitry must be examined in more detail. A third general area for further study is the effect of longer radiation pulses such as are produced by linear accelerators (1 μsec) or pulsed reactors (100 μsec). Finally it should be observed that it is desirable to undertake a more detailed quantitative investigation of the time dependence of the charge concentrations in the base region which produce the observed current components in the transistor. At the present time work is underway in each of these areas.

## ACKNOWLEDGMENTS

The authors particularly wish to acknowledge the helpful advice and suggestions received from G. L. Keister. In addition, G. C. Messenger and C. Rosenberg contributed significantly during many interesting discussions. G. G. Stevens provided valuable assistance with many of the measurements.

Two of us (D.S.G. and G.H.H.) wish to express our appreciation to the Boeing Company for the opportunity of working on this problem as College Faculty Associates during the summer of 1961.

This work was supported in part by U. S. Air Force contract AF 33(616)-7804 sponsored by the Advanced Research Projects Agency.

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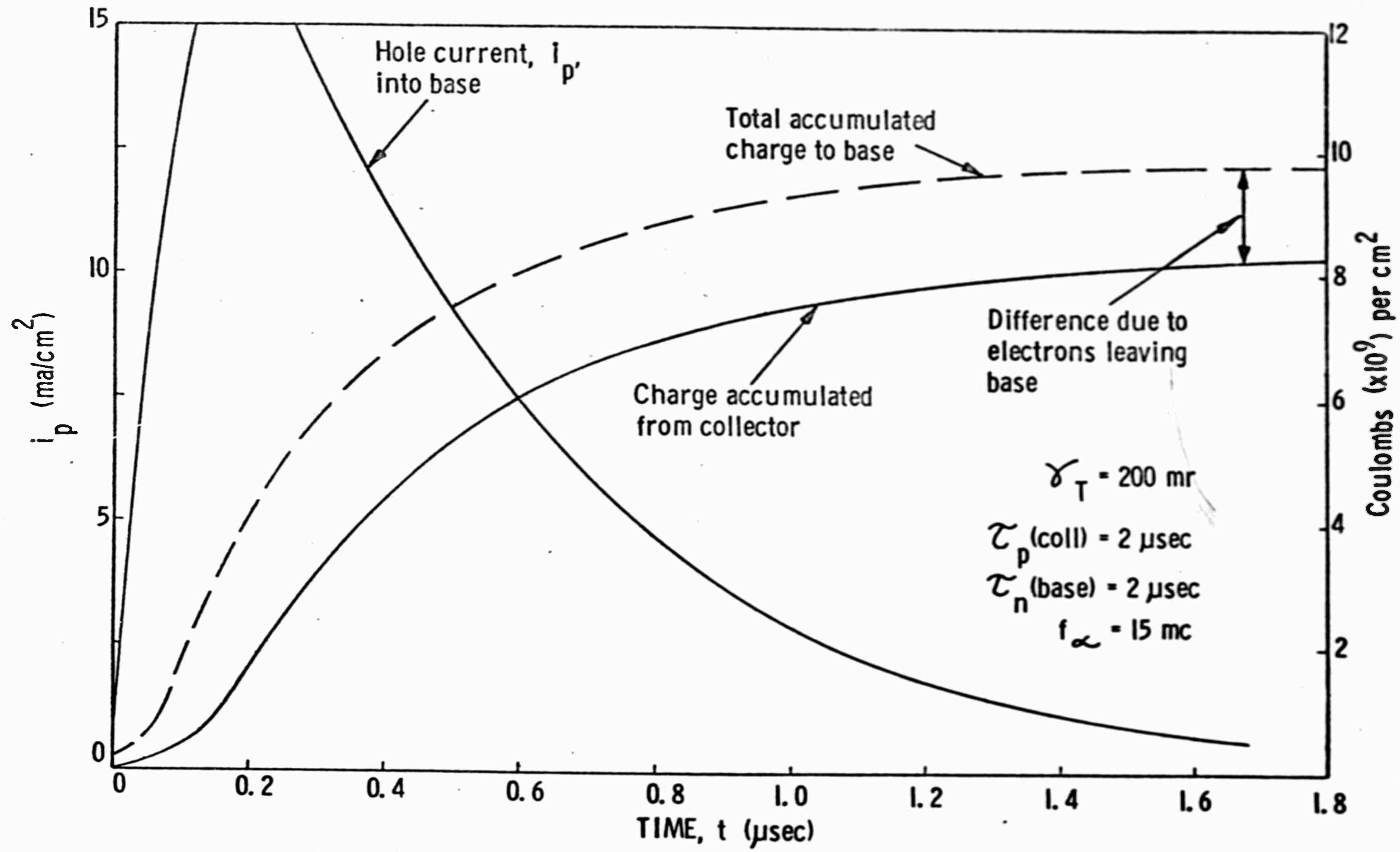


FIGURE 1. Calculated time dependence of hole current and accumulated charge for short lifetime grown-junction transistor.

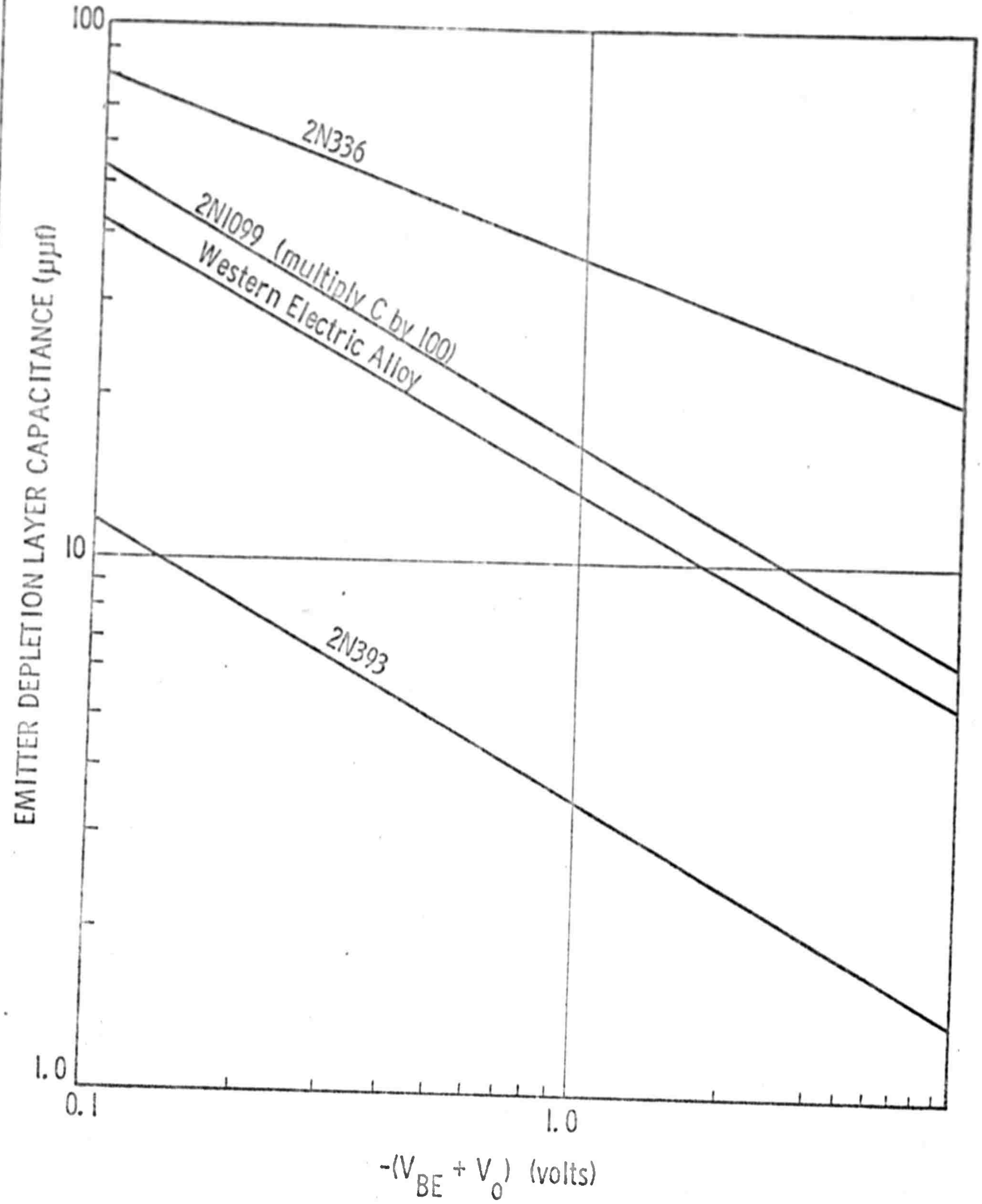


FIGURE 2. Voltage dependence of emitter depletion capacitance.

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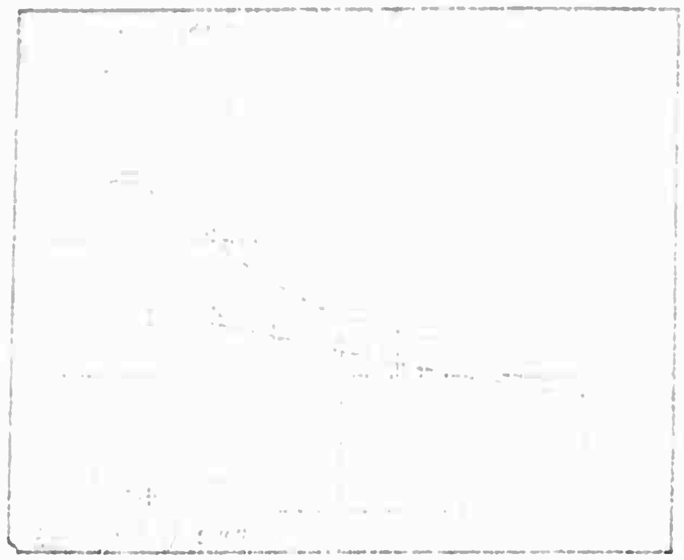

FIGURE 3. Current and voltage in a 2N336 transistor following irradiation by a 0.2 μsec X-ray pulse. (Upper trace: 500 μa/cm; Lower trace: 40 mv/cm; Time base: 0.5 μs/cm; $\gamma_T$ = 200 mr).

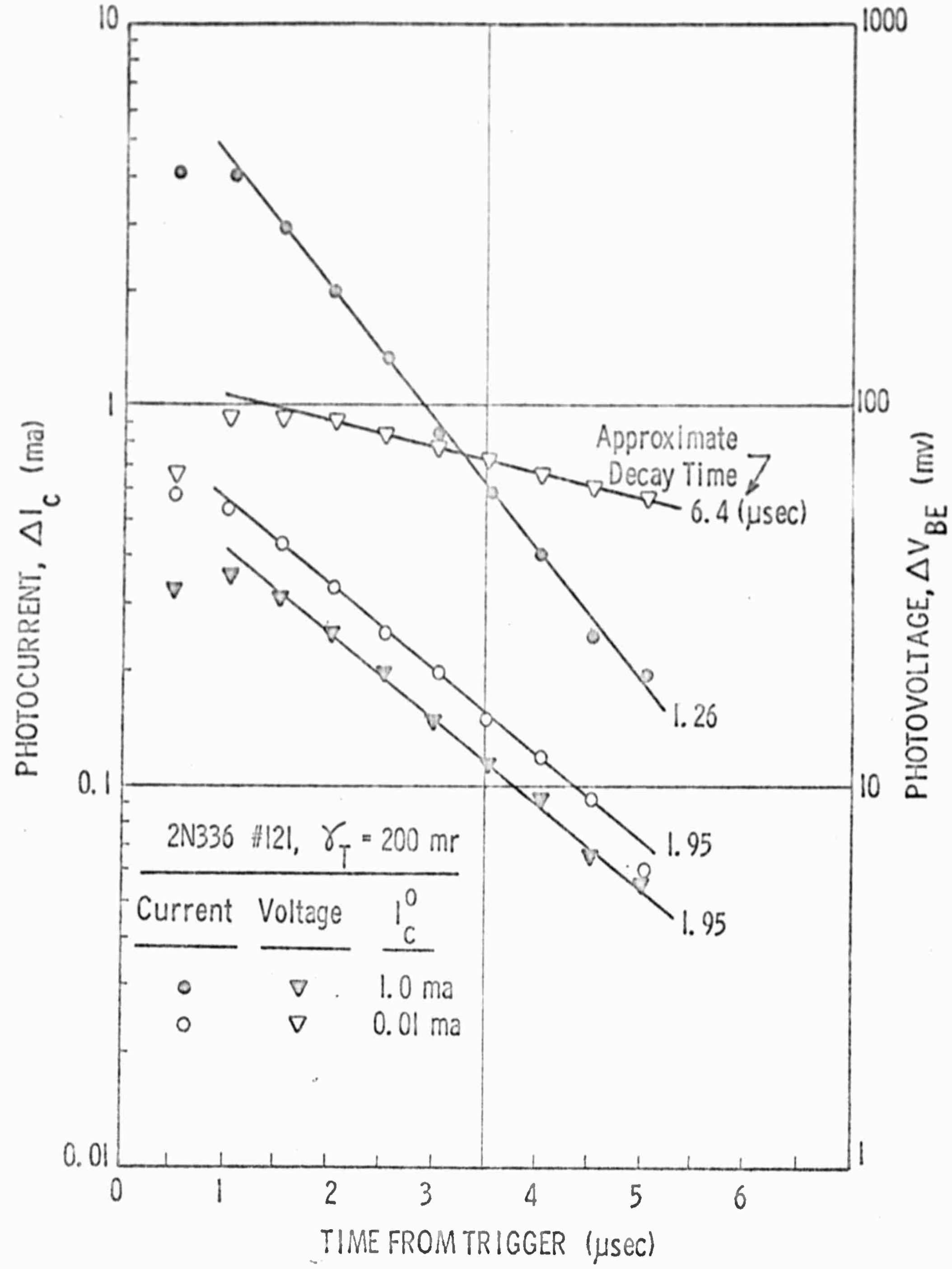


FIGURE 4. Decay times of observed photocurrents and photovoltages.

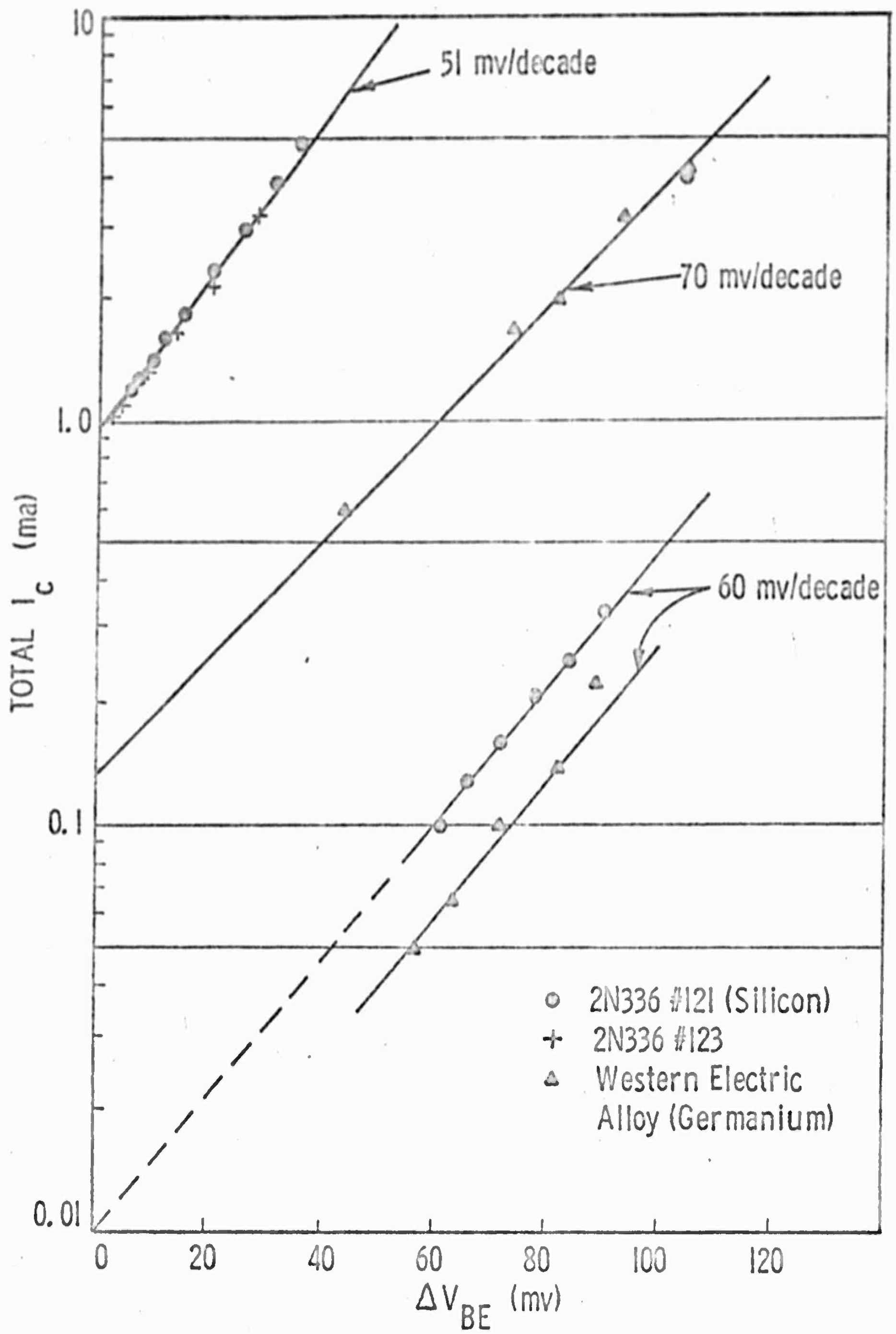


FIGURE 5. Measured emitter current-voltage decay curves following X-ray pulse.

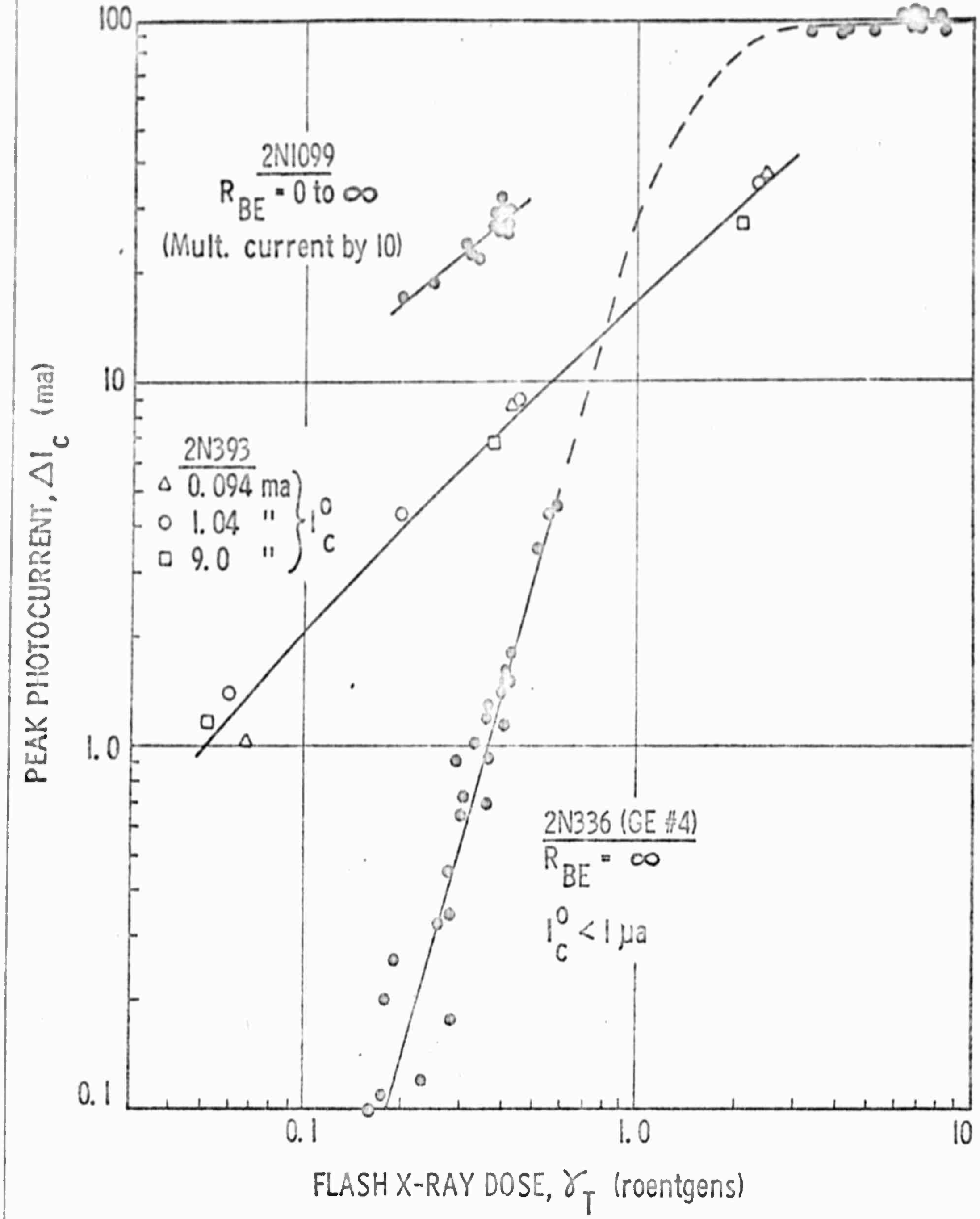


FIGURE 6. Peak photocurrent dependence on X-ray dose for three transistor types.

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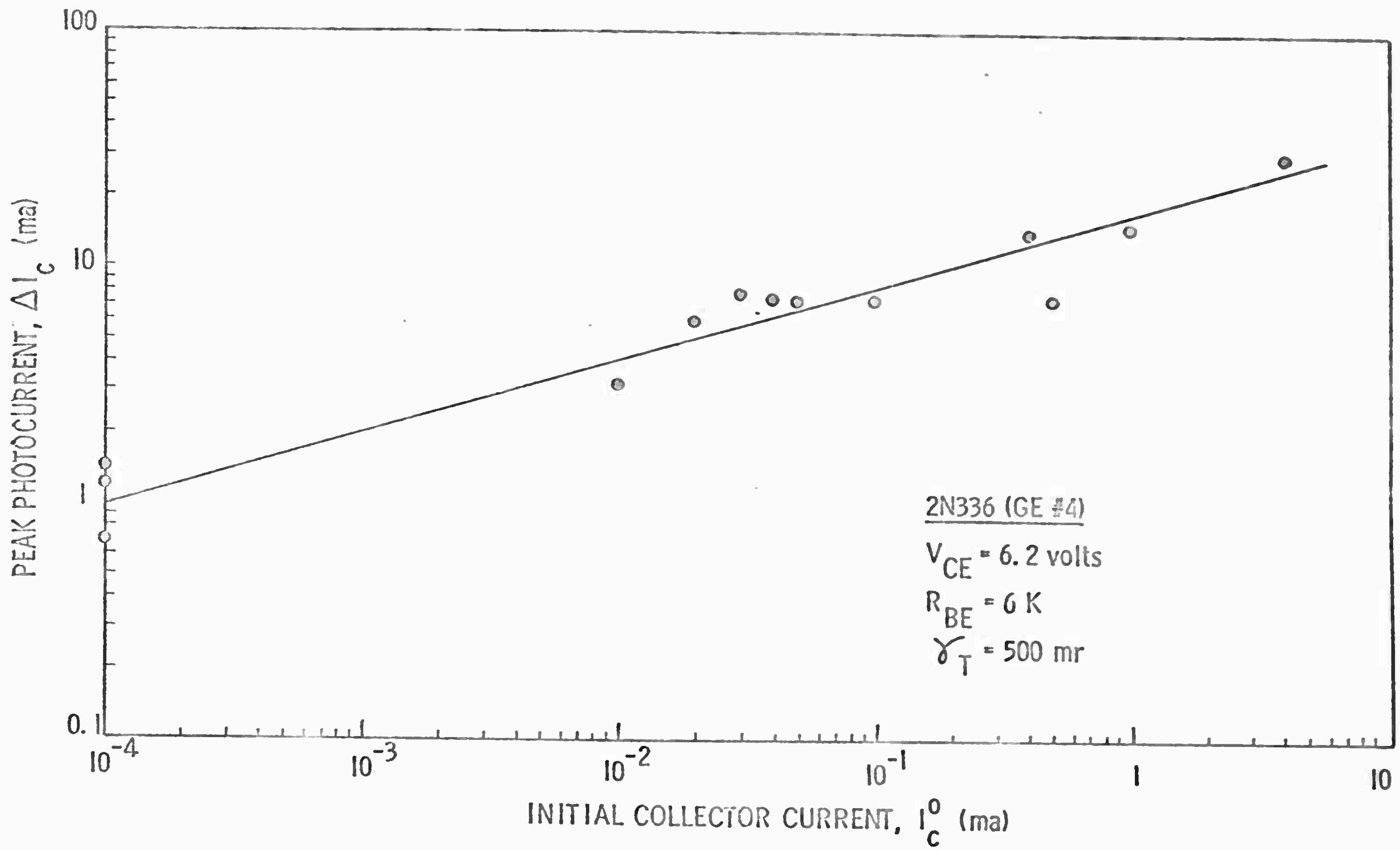


FIGURE 7. Dependence of photocurrent in 2N336 on initial current bias level.

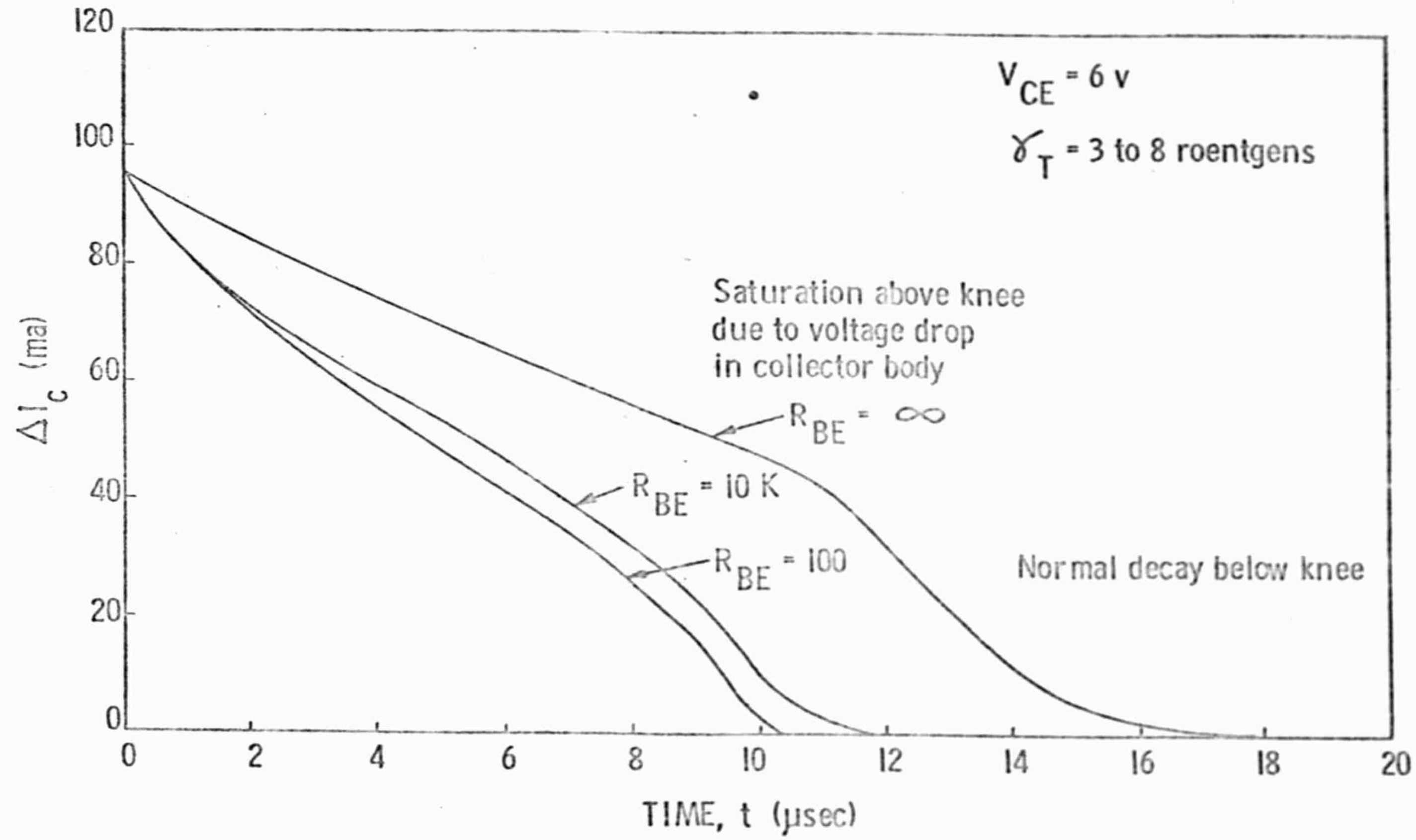


FIGURE 8. Saturation effects in 2N336.

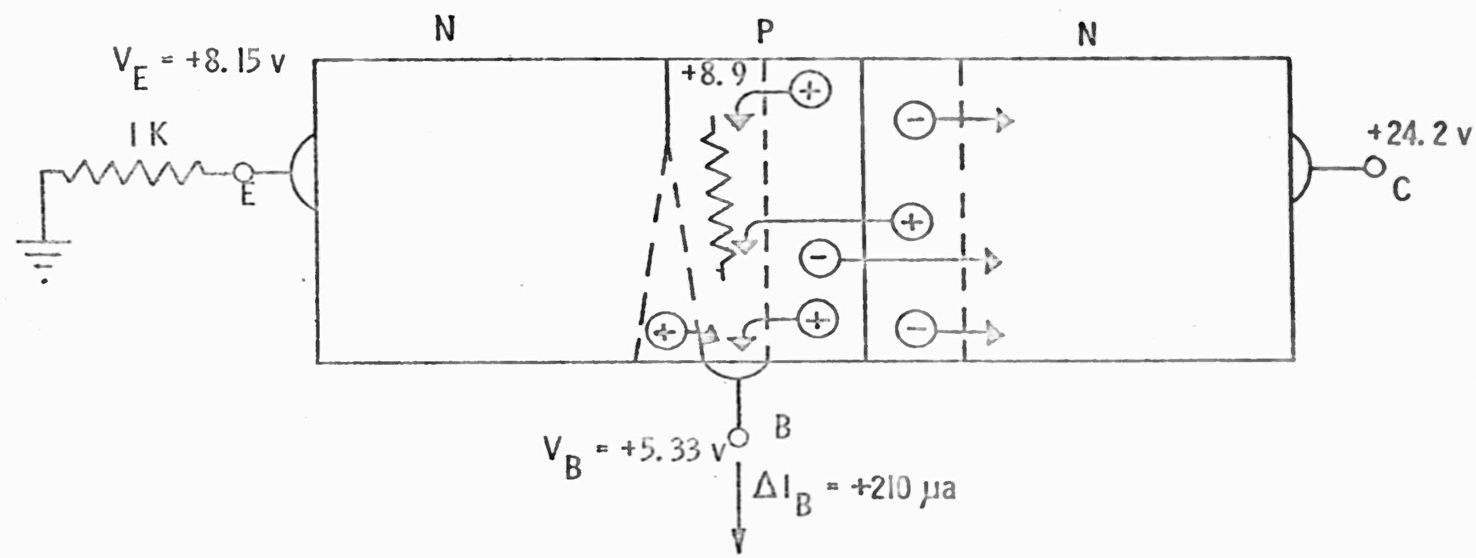


FIGURE 9. Details of voltage and current within a 2N336 transistor at the peak of a Kukla pulse reactor burst.

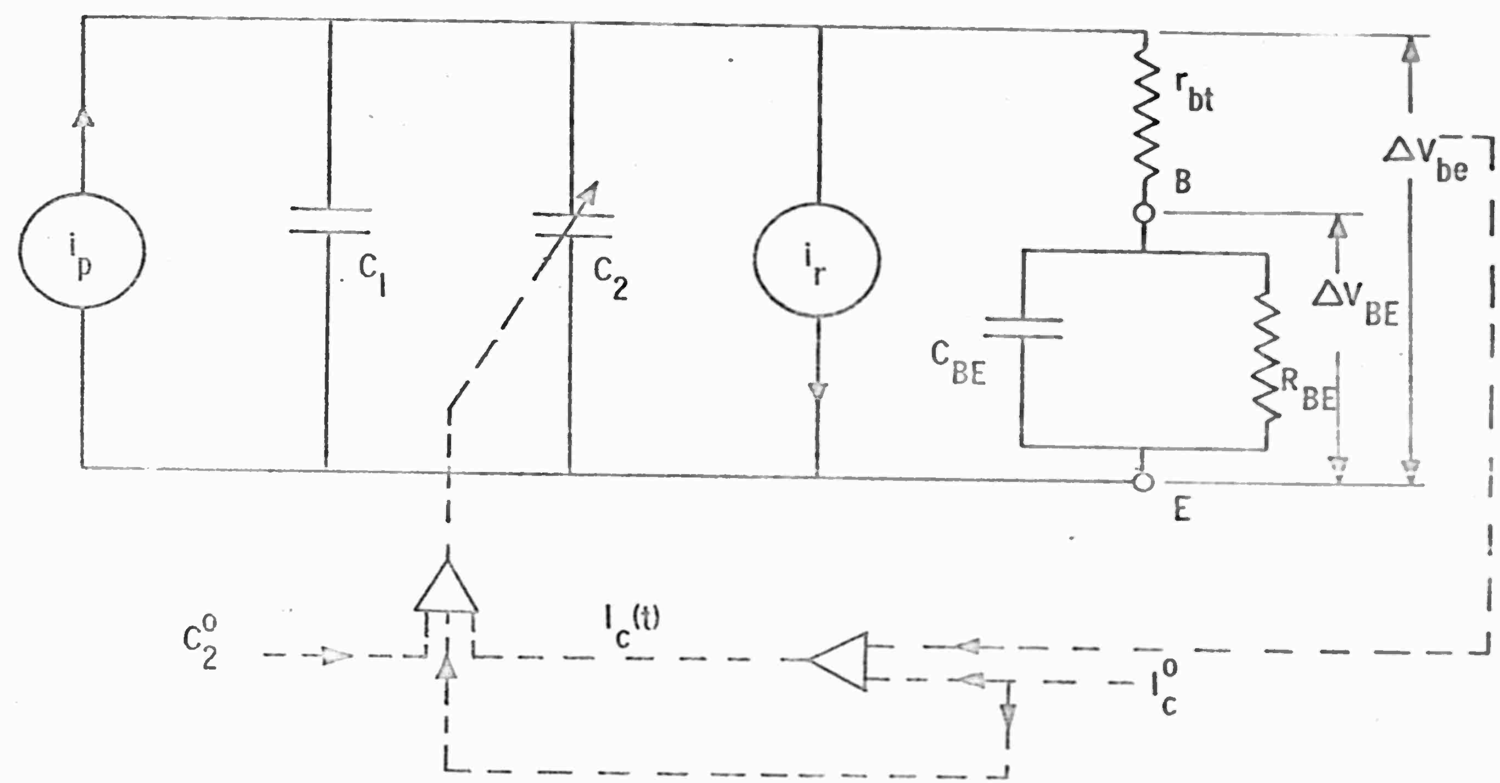


FIGURE 10. Equivalent circuit for predicting the radiation-induced transient current in transistors.